Galileo Orbit Determination During The Ida Encounter

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Introduction

After gaining sufficient energy during its last flyby with Earth on December 8, 1992, the Galileo spacecraft is on its way to Jupiter. En route. to Jupiter, Galileo successfully encountered asteroid 243-Ida on August 28, 1993, marking another milestone for the Galileo project. Ida now has become the second asteroid [o be visited by spacecraft. Galileo's encounter with the asteroid 951-Gaspra on October 29, 1991 was the first asteroid encounter. As the time of the Ida encounter approached, some unfortunate. circumstances occurred causing for a very worrisome but exciting encounter, especially with regards to navigation. In addition to the nominal 2-way S-band range and Doppler radiometric data obtained from the Deep Space Network (DSN), several navigational aids, were brought together to make this encounter successful. These include a thorough grou - based observation campaign of the asteroid during the four years prior to the flyby to significantly improve Ida's ephemeris, and the Optics] Navigation picture campaign which helped to significantly improve the uncertainties of Galileo's relative position to Ida. The experience gained from Galileo's encounter with Gaspra was also very helpful. This paper reports on Galileo's orbit determination strategy during the period after the. last Earth encounter through the Ida flyby. Details in the modeling of Galileo's orbit, and in the navigational tools described above will be explained, and the results of several key orbit solutions will be given.

Ida was discovered in 1884, by J. Palisa in Vienna. Ida is a member of the Koronis family of asteroids in the middle of the main asteroid belt. Based on Earth anti IRAS-based observations, Ida has been thought to be a relatively young S-Type asteroid with triaxial ellipsoid dimensions of 53 km by 23 km by 18 km. First clues from the Galileo's observations suggest Ida to be larger and much older than previously thought.

orbit Determination Strategy

When Galileo approached Earth for the last time on its Venus-Earth-Earth-Gravity-Assist (VEEGA) trajectory, it was targeted to Ida by obtaining a precise Earth flyby position at an altitude of 304 kilometers over the South Atlantic Ocean. It wasn't decided until after the last Earth flyby, however, to target the Ida flyby at a distance of 2400 km, 75° South ecliptic latitude through the darkside of Ida. Many nongravitational forces influenced Galileo's trajectory on its way to Ida;

these include solar pressure, unbalanced attitude turns, Retro-Propulsion Module (RPM) thruster line clearing flushes, and a practice probe delivery spin-up to 10 rpm and back down again to the nominal spin rate. Three trajectory collection maneuvers (TCM's) were planned to precisely achieve the desired target at Ida.

Galileo is nominally tracked by 2-way S-band Doppler and range radiometric data obtained by the 70 m DSN antennae in California, Spain, and Australia. The Doppler data type measures line-of-sight motion of the spacecraft relative to Earth through frequency shifts in the radio signal. Relative Earth-spacecraft distance is determined by the range data type which measures the round trip light-time of the uplink carrier signal modulated with a known digital code from the tracking station to the spacecraft and back to the station. Navigation based solely on radiometric data could not successfully guide Galileo to its target at Ida. Therefore, optical navigation (OPNAV) is required to insure a successful asteroid encounter. OPNAV consists of taking pictures of the asteroid against a background of stars. The angular separations between the asteroid and stars in each image is then measured to compute the spacecraft's relative position to Ida. The process of determining Galileo's orbit involves fitting a mathematical representation of Galileo's 01 bit to observed position, velocity information from the four types of data through a least squares method. Parameters such as spacecraft's initial state, solar radiation pressure, AV impulses are adjusted to minimize residuals between the observed and computed orbits using the Orbit Determinat ion Program (ODP), which uses a batch-sequential square root filtering algorithm.

Improvement of Ida's Ephemeris

The precise knowledge of Ida's orbit is essential to Galileo's successful navigation to its target aimpoint at Ma. Therefore, in addition to several decades of observations of Ida, special state-of-the-art CCD detectors, automatic measuring engines, sophisticate] data reduction techniques along with a selected group of experienced observers and special Lick Observatory reference star catalogs were employed to determine Ida's ephemeris with high precision. Astrometric observations of Ida obtained accuracies of better than O.? arc seconds during the 1992-93 period. The final observations included in this data set were reduced using two stars determined from the Hipparcos spacecraft and a plate overlap technique which obtained en-bit residuals of 0.06 arc seconds. Expressed in the Radial-Tran sverse-Normal (RTN) coordinate. frame where R represents the Sun-asteroid unit vector, N is unit vector normal to orbit plane, and 'I" is orthogonal to both R and N, the 1-σ uncertainty error ellipsoid of Ida's position at encounter was 44 km in the R component, 120 km in the T component and 81 km in the N direction. The semimajor axis of this ellipsoid is in the direction of the asteroid's motion which is closely defined by the '1' component. Since this and the N component errors represent plane of the sky motion as viewed from the. spacecraft, observations of Ida relative to Galileo using the OPNAV pictures help reduce these uncertainties significantly. The error in the R component cannot be reduced, however, through OPNAV. The uncertainty in Galileo's time of closest approach (C/A) with Ida is primarily determined by this error.

The Optical Navigation Strategy

The failure of Galileo's High Gain Antenna to open, severely impacted the number of OPNAV's that could be returned, The low data rate offered by the Low Gain Antenna (LGA) significantly lenghtened the time to return each OPNAV. The planned OPNAV campaign using the LGA consisted of shattering five pictures at 4'7, 37, 17, 11, and 7 days before C/A and were to be returned at 42, 33, 13, 8, and 5 days respectively before C/A. OPNAV uses a single-frame mosaic technique which involves leaving the camera shutter open while performing several small scan platform slews to capture multiple sets of asteroid and star images on one picture frame. The data weight given to each point on Ida's OPNAV images was 0.35 of a pixel based on experience from the Gaspra encounter. Each OPNAV was expected to contain at least eight points to use as individual measurements.

Results

Results of the encounter are presented in Ida's B-plane, defined as a plane centered at Ida and perpendicular to the approach asymptote. Figure 1 illustrates the components of the B-plane coordinate frame. The Ida B-plane aimpoint position originally selected for encounter was 2318 km in the B•R direction, –621 km in the. B•T direction and an encounter time on 28 August 1993, 16:51:00 UTC. The first maneuver m target to Ida's aimpoint, TCM- 19, occurred on March 9, 1993 with a AV of 2.12 m/s. Unfortunate] y, the spacecraft entered an automatic contingency mode prior to OPNAV 1, preventing OPNAV 1 from occurring. Therefore., instead of incorporating two OPNAV'S, the next maneuver, TCM-20, was designed with an orbit solution based on one OPNAV. The B-plane parameters for this orbit solution, OD #73, were 2956.95. 83.1 km in the B•R direction, -1073.0 ± 53.4 km in B•T with an encounter time at 28 August 1993, 16:51 :58.2 UTC ± 4.3 sec. To place Galileo back on target, the. execution of TCM-20, 15 days before C/A, required a AV of 0.618 m/s for a change in Ida's B-plane of 785.1 km and change in time of C/A of 1.42 seconds. Prior to OPNAV 3, the spacecraft once again entered the automatic contingency mode, thus losing OPNAV 3. Only 1/4 of OPNAV 5 was recovered before the DSN stations were directed to assist Mars observer during their pre-encounter anomaly. Therefore, the final orbit solution, OD #75, was based on two and one fourth OPNAV'S; this solution placed Galileo's encounter at 2328.6 ± 24.4 km in B•R, - 621.8 ± 13.9 km in B•T and time of encounter at 16:52:59.2 ± 3.91. This was considered sufficiently close to the desired target so that the. last maneuver at -2 days (TCM-21) was not necessary and thus cancelled. Figure 2 shows the Ida B-plane results for the OD #75 solution along with the targeted aimpoint. The success of this encounter can be exemplified by the high resolution picture of Ida received from Galileo. In addition, the location of the asteroid within the picture mosaic suggests that the orbit solution was better than anticipated.

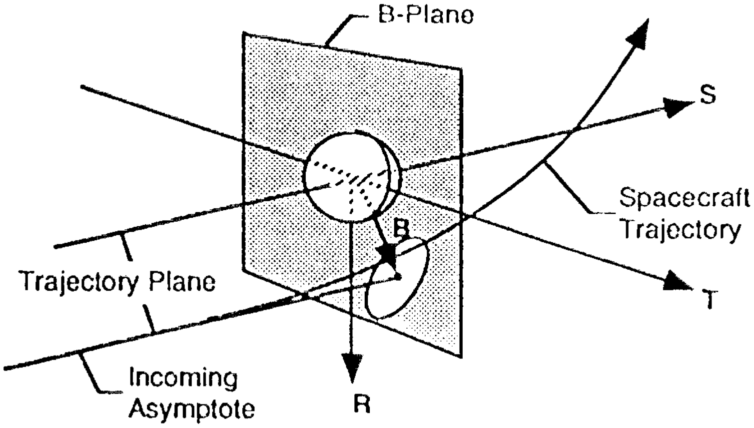

Figure 1: The definition of the B-Plane coordinate frame.

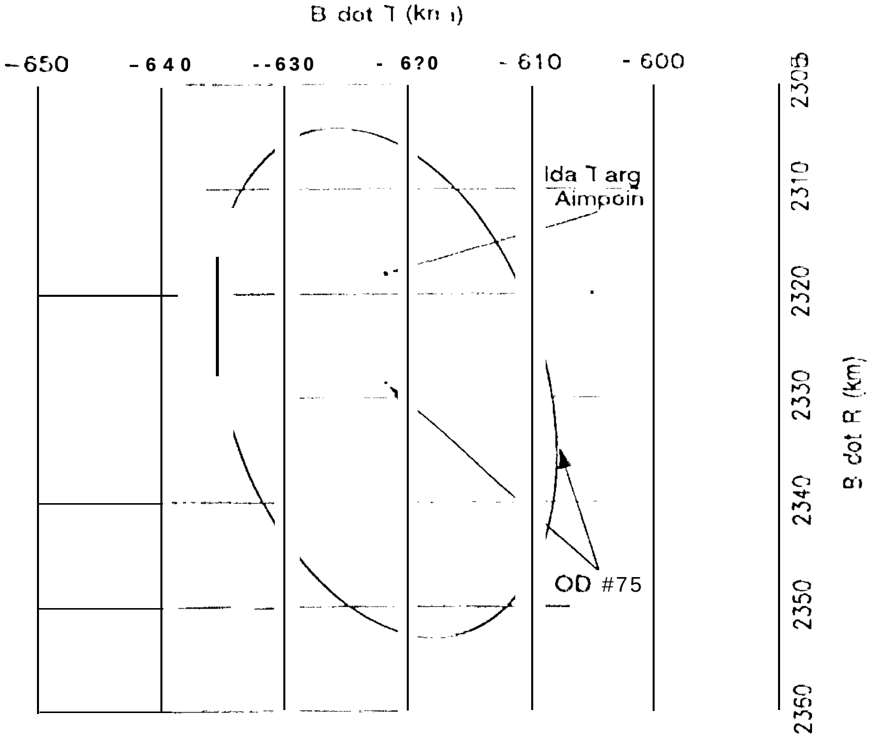

Figure 2: The Ma B-plane showing the target aimpoint and the final orbit solution, OD #75, with 1-0 uncertainty ellipse.